The Nexus between Cosmology and Elementary Particle Physics: Testing Theoretical Speculations through Observations of the Cosmic Microwave Background Anisotropies

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Abstract

The origin of the large scale structure in the universe — galaxies, quasars, clusters, voids, sheets — is one of the most important questions in cosmology. One can show that some non-thermal energy density fluctuations must have been present in the early universe. These fluctuations grew by gravitational instability to form the observed structures. There are at present two families of models to explain the origin of these initial fluctuations: inflationary models and topological defect scenarios. Current observational developments provide a link with theoretical predictions, allowing us to test our theoretical models. In this contribution, I present a sketch of the current status of the origin of cosmological structure formation.

1 Introduction

At present, our understanding of the evolution of the observed universe rests on the hot big bang model, which, being particularly successful, is considered as the standard cosmology. In favor of this model, there is direct evidence which extends back to about 10^{-2} sec after the explosion, at the onset of primordial nucleosynthesis. Combining theories of fundamental physics at ultra-high energies, with the notion that standard cosmology is very robust, allows us to speculate about the history of our universe at times as early as 10^{-43} sec after the bang.

The standard cosmology, described by the Friedmann-Robertson-Walker metric, lies upon three theoretical pillars: (i) the Einstein's general theory of relativity, which determines the dynamics of the universe; (ii) the cosmological principle, which states that the universe is homogeneous and isotropic on large scales; and (iii) a perfect fluid description of the matter content. On the other hand, its main observational pillars consist of: (i) the Hubble's redshift-distance relation, showing that the universe is expanding; (ii) the existence of a blackbody cosmic microwave background, discovered in 1965 by Penzias and Wilson [1]; and (iii) the agreement between observed and theoretically determined, according to nucleosynthesis, abundances of light elements.

Despite its successes, the standard big bang model faces a number of unanswered questions, like the requirement up to a high degree of accuracy of an initially homogeneous and flat universe, the origin of the observed large scale structure, the small value of the cosmological constant, the nature of the dark matter; as well as the problem of the age of the universe, a possible conflict between theory and observations.

An appealing solution to the homogeneity and flatness problems is to introduce, during the very early stages of the universe, a period of exponential expansion known as inflation [2]. According to the inflationary paradigm, the expansion of the universe was driven, at an early stage of its history, by a scalar field. During that period the expansion was quite dramatic, and the quantum fluctuations of the scalar field [3] were enormously amplified when that phase ended. Thus, inflation provides a mechanism [4] for the causal generation of the primordial density perturbations required for the observed large scale structures.

Inflationary models are not entirely free from problems and therefore it is important to address the issue of the origin of structure formation according to some other theory. The main alternative approach lies on the topological defect scenarios, based on the idea that a number of cosmological phase transitions took place, as the universe cooled down, associated with spontaneous symmetry breakings of the previous phase. Therefore, topological defects — a well-studied phenomenon in condensed matter physics — could have appeared in our universe [5] and played the role of seeds for structure formation. Topological defect models have the advantage of depending on very few parameters and therefore are, in a sense, more appealing than the inflationary ones. Depending on the nature of the broken symmetry, topological defects can either be local or global, while their classification depends on the number of components of an order parameter which breaks the symmetry group. Among the various topological defects, global monopoles, global textures and both global or local cosmic strings, are viable candidates. Since the initial density fluctuations have tiny amplitudes, their evolution at early times can be studied using linear cosmological perturbation theory.

2 Cosmic Microwave Background Radiation

The Cosmic Microwave Background (CMB) radiation is the extraterrestrial electromagnetic radiation that uniformly fills the space at wavelengths in the range of millimiters to centimeters. At present, the spectrum of CMB radiation is, to a high degree of accuracy, a thermal Planck blackbody spectrum at a temperature [6] $T_0 = 2.728 \pm 0.002K$, as measured by the FIRAS (Far Infrared Absoulute Spectrophotometer) on the COBE (Cosmic Background Explorer) satellite developed by NASA. Since now the universe is optically thin to radio radiation, the sea of CMB radiation, having almost completely relaxed to thermodynamic equilibrium, must be the remnant heat from the early hot and dense phase of the expanding universe.

The existence of the CMB radiation with an almost thermal nature consists the main evidence that the universe did indeed expand from a dense and hot state. In addition, the CMB radiation is extremeley close to isotropic; this uniformity cannot be explained within the context of standard cosmology. The CMB radiation offers an essential probe of the origin of structure formation, through the effects of cosmological structure on the spectrum and isotropy of the relic CMB radiation.

In 1992, the COBE-DMR (Differential Microwave Radiometer) experiment detected anisotropies (temperature irregularities) in the CMB radiation [7]. These anisotropies, imprinted on the CMB radiation by primordial perturbations generated within 10^{-35} sec after the big bang, were found to be at the level $\Delta T/T \approx 1. \times 10^{-5}$ on all angular scales larger than 10^o and compatible with a scale invariant (spec-

tral index of $n_s = 1.2 \pm 0.3$ [8]) Harrison-Zel'dovich spectrum. While confirming the idea that indeed large structures grew from small initial fluctuations through gravitational instability, the COBE-DMR observations could not discriminate between inflationary models and topological defect scenarios. The planned MAP (Microwave Anisotropy Probe) and COBRAS/SAMBA (COsmic Background Radiation Anisotropy Satellite / SAtellite for Measurement of Background Anisotropies) satellite experiments, as well as ballons and ground based experiments, will probe anisotropies on smaller angular scales, which may allow us to distinguish between these two classes of models for structure formation. Such experiments show how the early universe offers an ideal laboratory to test high energy physics models, on energy scales far beyond those of any conceivable terrestrial accelerator. Moreover, from the point of view of a cosmologist, the CMB radiation offers the unique way of determining basic cosmological parameters — like $\Omega_0, H_0, \Omega_b, \Lambda$ — to within a few percent, through measurements of the CMB anisotropy spectrum. The justification for this belief is mainly that CMB anisotropies can be determined almost fully within linear cosmological perturbation theory and are not particularly affected by nonlinear physics.

The CMB fluctuation spectrum is usually parametrized in terms of multiple moments C_ℓ, defined as the coefficients in the expansion of the temperature autocorrelation function

$$\langle\frac{\delta T}{T}(\mathbf{n})\frac{\delta T}{T}(\mathbf{n}')\rangle\Big|_{(\mathbf{n}\cdot\mathbf{n}'=\cos\vartheta)} = \frac{1}{4\pi}\sum_\ell(2\ell+1)C_\ell P_\ell(\cos\vartheta)\ , \tag{1}$$

which compares points in the sky separated by an angle ϑ. The value of C_ℓ is determined by fluctuations on angular scales of order π/ℓ. One usually plots $\ell(\ell+1)C_\ell$ versus ℓ — known as the power spectrum — which is the power per logarithmic interval in ℓ, giving the spectrum of anisotropies observed today.

For scalar perturbations, I will describe the main physical mechanisms which contribute to the redshift of photons propagating in a perturbed Friedmann geometry.

(i) On large angular scales, the main contribution to CMB anisotropies comes from inhomogeneities in the spacetime geometry. These inhomogeneities determine the change in the photon energy, due to the difference of the gravitational potential at the position of emitter and observer, and account for red-shifting or blue-shifting, caused by the time dependence of the gravitational field along the path of the photon. They are known as "ordinary" Sachs-Wolfe and Integrated Sachs-Wolfe (ISW) effects respectively.

(ii) On angular scales $0.1^\circ \lesssim \theta \lesssim 2^\circ$, the main contribution comes from the intrinsic inhomogeneities on the surface of the last scattering, due to acoustic oscillations in the coupled baryon-radiation fluid prior to decoupling. On the same angular scales as this acoustic term, there is a Doppler contribution to the CMB anisotropies, due to the relative motions of emitter and observer. The sum of these two contributions is denoted by the term "acoustic peaks".

(iii) On scales smaller than about 0.1°, the anisotropies are damped due to the finite thickness of the recombination shell, as well as by photon diffusion during recombination (Silk damping).

Both, generic inflationary models and topological defect scenarios, predict an approximately scale-invariant spectrum of density perturbations on large angular scales ($\ell \lesssim 50$), thus the COBE-DMR data provide mainly a normalization for the different models. Cosmic microwave background anisotropies on intermediate and small angular scales are very important. If the two classes of theories predict different characteristics for the acoustic peaks (e.g., amplitude and position of primary peak, existence or absence of secondary peaks) we can discriminate among them. In the

nearby future, a number of sophisticated experiments will scrutinize various regions of the sky trying to reveal the characteristics of the relic CMB radiation.

3 Families of Models for Structure Formation

Within the framework of gravitational instability theory, there are two currently investigated families of models to explain the origin of the observed structure in the universe.
(i) Initial density perturbations can be due to freezing in of quantum fluctuations of a scalar field during an inflationary era [9]. Such fluctuations were produced at a very early time in the history of the universe, and were driven far beyond the Hubble radius by the enormous (inflationary) expansion. As a result, inflationary fluctuations are not altered anymore and evolve freely according to homogeneous linear perturbation equations until basically the time of galaxy formation. Moreover, as a result of the nature of quantum fluctuations, the distribution of amplitudes of these initial perturbations is usually Gaussian.
(ii) Initial density perturbations can be seeded by an inhomogeneously distributed form of energy, called "seed", which contributes only a small fraction to the total energy density of the universe and which interacts with the cosmic fluid only gravitationally. A familiar example is the case of topological defects, which could have appeared naturally during a symmetry breaking phase transition in the early universe [5]. According to these models, cosmological structure was formed as a result of a symmetry breaking phase transition and a phase ordering. Such initial fluctuations are generated continuously and evolve according to non-homogeneous linear perturbation equations. Perturbations from defect models are generally non-Gaussian.

On large angular scales, both families of models predict an approximately scale-invariant Harrison-Zel'dovich spectrum [10, 11], the Sachs-Wolfe plateau. The acoustic peaks on intermediate scales in the CMB power spectrum, might represent a mean to support or rule out one of these two families of models.

In the case of inflationary models, there has been a large number of studies and a lot of excitement, in particular since CMB anisotropies might lead to a determination of fundamental cosmological parameters, such as the spatial curvature of the universe Ω_0, the baryon density Ω_b, the Hubble constant H_0 and the cosmological constant Λ. At multipoles $\ell \geq 200$, the CMB anisotropies become sensitive to fluctuations inside the Hubble horizon at recombination. Since these fluctuations had enough time to evolve prior to last scattering, they are sensitive to evolutionary effects that depend on a number of cosmological parameters. The new generation of satellites (MAP and especially COBRAS/SAMBA) having high sensitivity, angular resolution and large sky coverage, are expected to provide a mean to determine these fundamental cosmological parameters to a precision of a few percent.

The power spectrum predicted for a generic inflationary model reveal the existence of a primary peak at $\ell \sim 200$ with an amplitude $\sim (4-6)$ times the Sachs-Wolfe plateau, and the existence of secondary oscillations [9].

On the other hand, seed models (like topological defect models), generally predict a quite different power spectrum than inflation, due to the behaviour of perturbations on super-horizon scales. Causality and scale invariance have quite different implementations in this class of models. While in inflationary models randomness appears only when initial conditions are set up and the time evolution is linear and deterministic, in seed models randomness also appears during the time evolution, as a result of a complex non-linear process. Seed models are more complicated to be solved than inflationary ones, due to the fact that the linear perturbation equations are non-homogeneous with a source term due to the seed. Since the seed evolution

is, in general, a non-linear and complicated process, much less precise predictions have been made so far, and there is a limited number of studies on the family of seed models.

Recent studies [12, 13, 14] on generic topological defect models show that the primary acoustic peak is located to the right of the adiabatic position, at which the peak arises in a generic inflationary model. The value of this shift to smaller angular scales is determined by the coherence length of the defect. Also the structure of secondary peaks may be quite different for generic defects as compared to inflation. Depending on whether the defect is effectively coherent or not, which is a direct implication of the constraints imposed by causality on defect formation and evolution, secondary peaks will or will not appear in the power spectrum [14]. Considering density perturbations seeded by global textures, π_3 defects [15], in a universe dominated by cold dark matter, the position of the primary acoustic peak was found to be displaced by $\Delta\ell \sim 150$ towards smaller angular scales than in standard inflationary models [12, 13], while its amplitude was only a factor of $\sim 1.5 - 3.3$ times higher than the Sachs-Wolfe plateau [13]. In an attempt to reveal the robust features of the power spectrum in a seed model, it was found [16, 17] that there are defect models leading to a primary acoustic peak located at the adiabatic position, however its amplitude may be susbtantially smaller than the one in generic inflationary models [17].

The satellites MAP and, in particular, COBRAS/SAMBA with planned launch years around 2000 and 2005 are designed to image anisotropies of the CMB radiation to an uncertainty better than $\Delta T/T \sim 2 \times 10^{-6}$ at all angular scales larger than $\sim$ 10 arcmin over the whole sky. We therefore expect to have a full power spectrum against which we could test our theoretical models.

4 Conclusions

The nexus between cosmology and elementary particle physics has become an especially active area of research in recent years. Current frontiers of particle physics involve energy scales far beyond those available now or in the near future terrestrial particle accelerators. An obvious place to look is to the very early universe, where conditions of extreme energy and density are realized. At the same time, the standard big bang model provides a reliable framework for describing the evolution of our universe as early as 10^{-2} sec after the explosion, when the temperature was about 10 MeV. Extending our understanding to earlier times and higher temperatures, requires knowledge about the fundamental particles and their interactions at very high energies; progress in cosmology has become linked to progress in particle physics.

Among the main, still open problems in modern cosmology, remains the origin of the observed structure in the universe. Based on all present indications, we believe that the large-scale structure was produced by gravitational instability from small primordial fluctuations in the energy density, generated during the early stages of the universe. Within this framework, the two families of models to explain the origin of primordial density perturbations are inflationary models and topological defect scenarios. Either of these two families of models predicts precise fingerprints in the cosmic microwave background anisotropies, which can be used to differentiate among these models using a purely linear analysis. Both families lead to approximately scale-invariant Harrison-Zel'dovich spectrum of density fluctuations on large angular scales. However, the power spectrum predicted from each of these families, has different properties on smaller angular scales. The next satellite experiments (MAP and COBRAS/SAMBA), as well as ground-based (e.g., Jodrell Bank, CAT, SASKATOON, VSA) and ballons experiments (e.g., BOOMER, FIRS, MAX, MAX-

IMA, MSAM, UCSB) will provide a detailed power spectrum, against which we will be able to test our theoretical models. In addition, we expect to be able to determine a number of fundamental cosmological parameters up to a high degree of accuracy. It is therefore believed that these coming years will be particularly fruitful for cosmology and one may conclude that as cosmologists we are currently living through what can be considered a scientific revolution.

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